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Modelling bioactivity and degradation of bioactive glass based tissue engineering scaffolds

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ABSTRACT

Bioactive glasses are a class of inorganic biomaterials widely used in bone tissue engineering and regenerative medicine. Once implanted in the human body, these biomaterials react with the body fluid resulting in the formation of a surface hydroxyapatite (HA) layer, which exhibits the ability to form a stable chemical bond with the adjacent living bone tissue. The experimental evaluation of the degradation of bioactive glasses in contact with body fluid requires long-term in vitro assays. In this work, a novel mathematical model is proposed to numerically analyze the dissolution and bioactivity of bioactive glasses in relevant conditions for their in vitro and in vivo applications. A detailed framework is described for the numerical implementation using the Voxel-FEM method, in order to account for the microstructural evolution as consequence of degradation and HA layer formation. Two examples of application are highlighted, showing the suitability and usefulness of the proposed model for the evaluation of bioactive glasses in tissue engineering applications.

1. Introduction

Bioactive silicate glasses were discovered by Hench et al. (1971) almost 40 years ago. When implanted in the human body, these glasses react with the body fluid, which dissolves the glasses through complex surface physico-chemical reactions. Glass dissolution releases a cascade of ions, which in turn react with the body fluid finally resulting in the formation of a surface hydroxyapatite (HA) layer. Due to the presence of this layer, the biomaterial exhibits the ability to form stable chemical bonds with the adjacent living tissue (Hench et al., 1971; Hench, 1998). This particular behaviour is known as 'bioactivity' in the specialised literature (Kokubo et al., 1990). One of the most popular bioactive glasses has the composition 45 wt.% SiO_2, 24.5 wt.% Na_2O, 24.5 wt.% CaO and 6 wt.% P_2O_5, and it is known as 45S5 Bioglass® (Hench et al., 1971). This bioactive glass has been the base material for many developments in the framework of (non-load bearing) orthopaedic implants, dental materials as well as regenerative medicine and bone tissue engineering, showing promising results in several cases and applications (i.e., see Chen et al., 2006a; Hench and Paschall, 1973; Hench et al., 1991; Hench and West, 1996; Rezwan et al., 2006; Roether et al., 2002a,b; Wilson and Low, 1992; Wilson et al., 1993; Yamamuro, 1990).

The intrinsic behaviour of bioactive glasses has placed these materials as perfect candidates for fabrication of scaffolds for bone tissue engineering applications (Chen et al., 2006a; Hench and Polak, 2002; Rezwan et al., 2006; Roether et al., 2002a). In this field, highly porous scaffolds are used as substrates to promote new bone tissue formation. Among many requirements, the scaffold should be porous with adequate pore size, exhibit tailored degradation/dissolution and must be strong enough to support mechanical loads (mainly in bone tissue applications) (Guarino et al., 2007; Hutmacher, 2000; Jerome and Maquet, 1997; Wake et al., 1994). Fabrication techniques to produce suitable porous scaffolds from bioactive glasses (and glass–ceramics) have been reported (Chen et al., 2006a; Fu et al., 2007; Livingston et al., 2002; Vitale-Brovarone et al., 2007).

In terms of structural integrity, bioactive glasses are not optimal materials due to their intrinsic brittleness (Chen et al., 2006a). Some solutions in this context are either forming a crystalline phase in the bioactive bulk glass, effectively developing glass–ceramics (Chen et al., 2006a; Vitale-Brovarone et al., 2007), or introducing a different phase (usually a polymer), forming a composite (Yunos et al., 2008).

Scaffold performance evaluation is crucial to ensure a well-designed tissue engineering scaffold. Experimental protocols may

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